Doped Liquid Argon TPCs as a $0\nu\beta\beta$ Platform

Fernanda Psihas

Fermilab

A. Mastbaum, F. Psihas, J. Zennamo. <u>arXiv:2203.14700</u>
"Xenon-Doped Liquid Argon TPCs as a Neutrinoless Double Beta Decay Platform" ***Submitted to PRD***

Snowmass Summer Study

Takeaways

A **Neutrino-less double-beta decay** discovery would elucidate questions about the neutrino mass mechanism & limits to the half-life are intertwined with the question of the **neutrino mass ordering**.

A doped LArTPC could have significantly expanded the DUNE physics reach and is **compatible** with other low energy concepts

This concept **introduces many R&D questions,** of which comprise a rich research program for the coming decade

Some References

enabling neutrino-less double-beta decay

Xenon-Doped Liquid Argon TPCs as a Neutrinoless Double Beta Decay Platform

A. Mastbaum,[1] F. Psihas,[2] and J. Zennamo[2]

[1] *Rutgers University, Piscataway, NJ, 08854, USA*
[2] *Fermi National Accelerator Laboratory (FNAL), Batavia, IL 60510, USA*
(Dated: March 29, 2022)

LArTPC R&D For DUNE & beyond

Snowmass2021 - Letter of Interest

Improving Large LArTPC Performance Through the Use of Photo-Ionizing Dopants

Topical Group(s):
(NF10) Neutrino detectors
(IF08) Noble Elements

Authors: J. Zennamo, A. Mastbaum, F. Psihas

Photo-ionizing LAr

Jul 20, 2022, 11:22 AM
19m
110 (Kane Hall)

Neutrino Physics Front...

Speaker

Fernanda Psihas Olmedo (Fermi National Acce...

Photo-ionizing Dopants

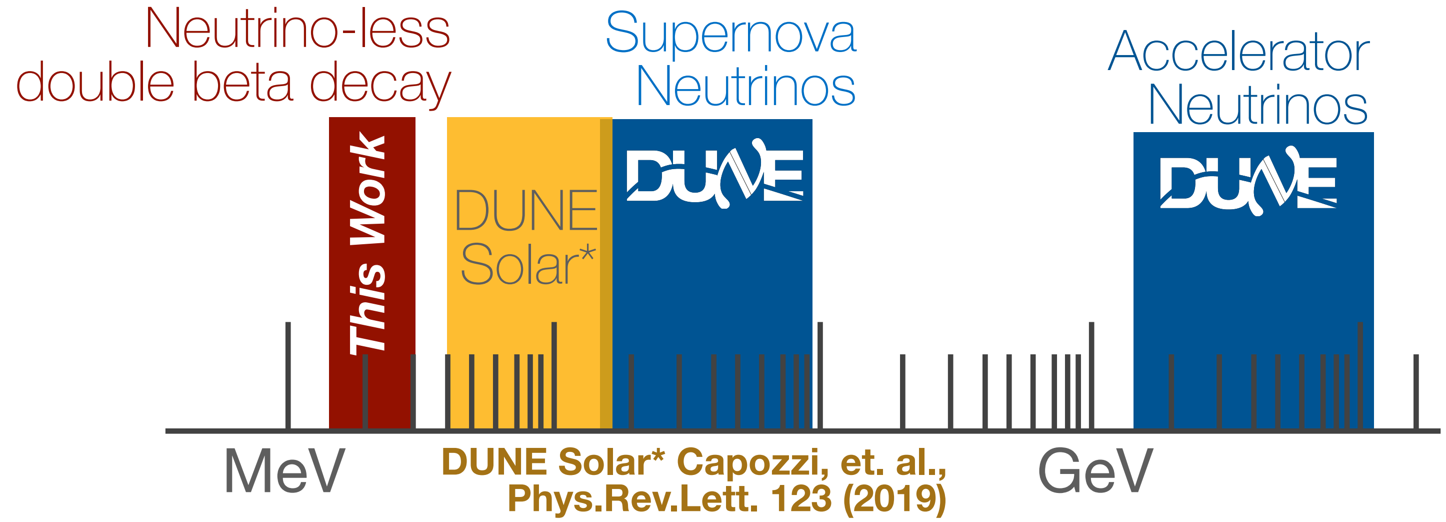
Jul 23, 2022, 9:00 AM
15m
026 (JHN)

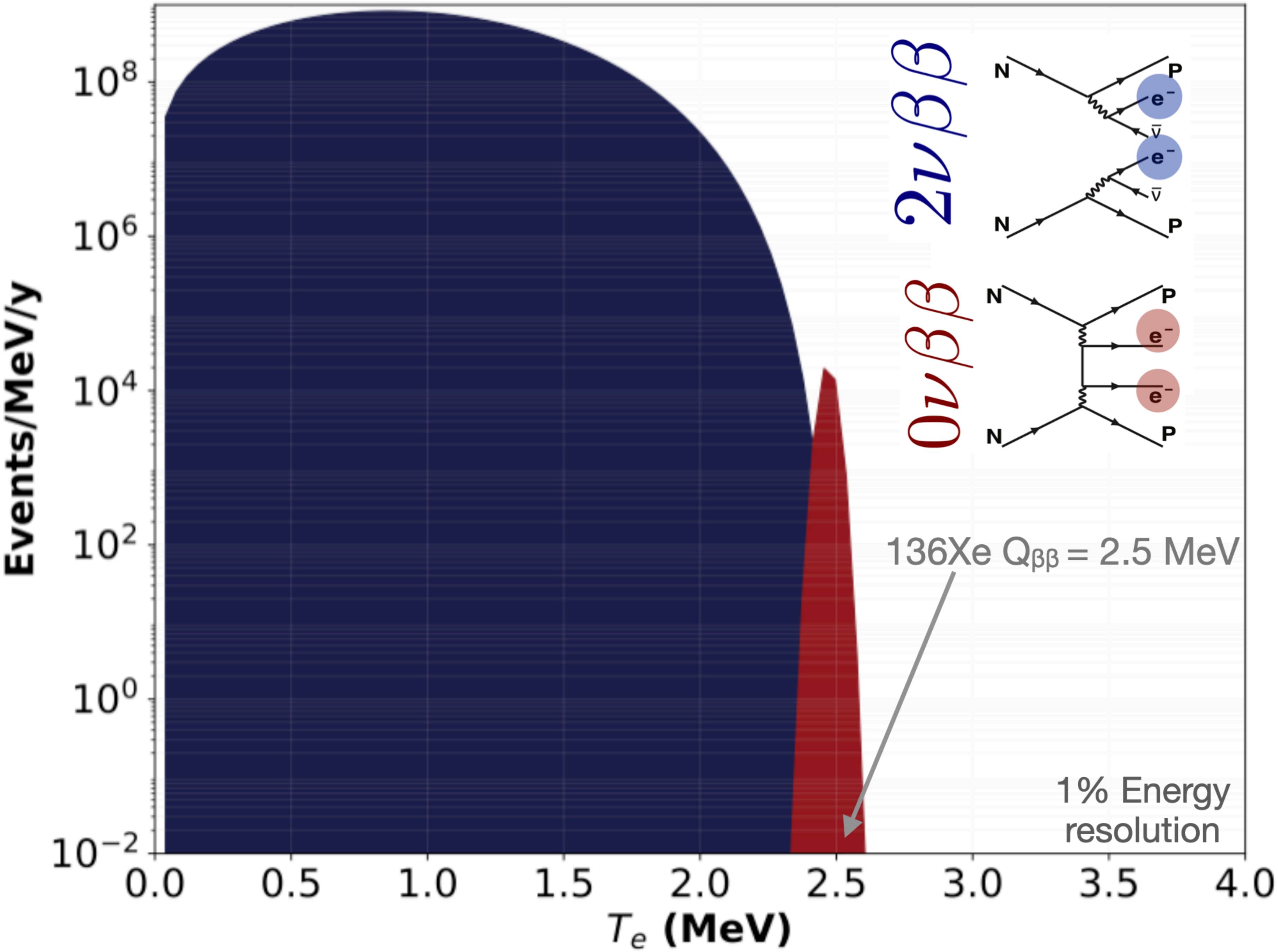
Cross Frontier Sessions

Speaker

Joseph Zennamo (Fermilab)

Signal ID and measurement





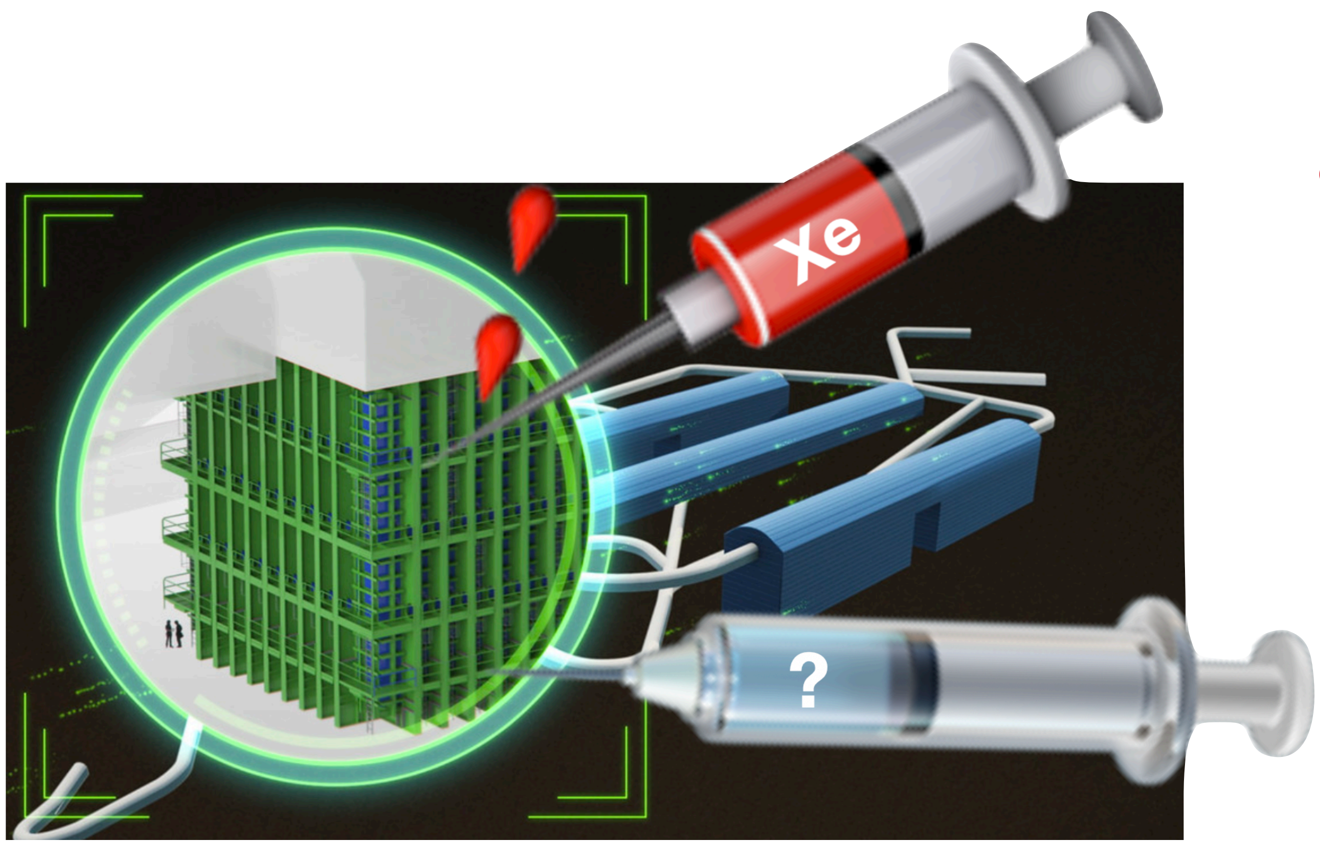
Signal is 2 electrons with energy = $Q_{\beta\beta}$

The $2\nu\beta\beta$ background is irreducible without precise energy measurement

GOALS

To **enable 0νββ** (neutrino-less double-beta decay) searches in LArTPCs
Reach sensitivities in the **normal ordering region of $m_{\beta\beta}$** phase space
To **enhance the low energy physics** reach of LArTPCs

A. Mastbaum, F. Psihas, J. Zennamo "Xenon-Doped Liquid Argon TPCs as a Neutrinoless Double Beta Decay Platform" arXiv:2203.14700



Dope with ^{136}Xe at 2%, which is a 0νββ candidate isotope

Dope with a photosensitive dopant to improve energy resolution

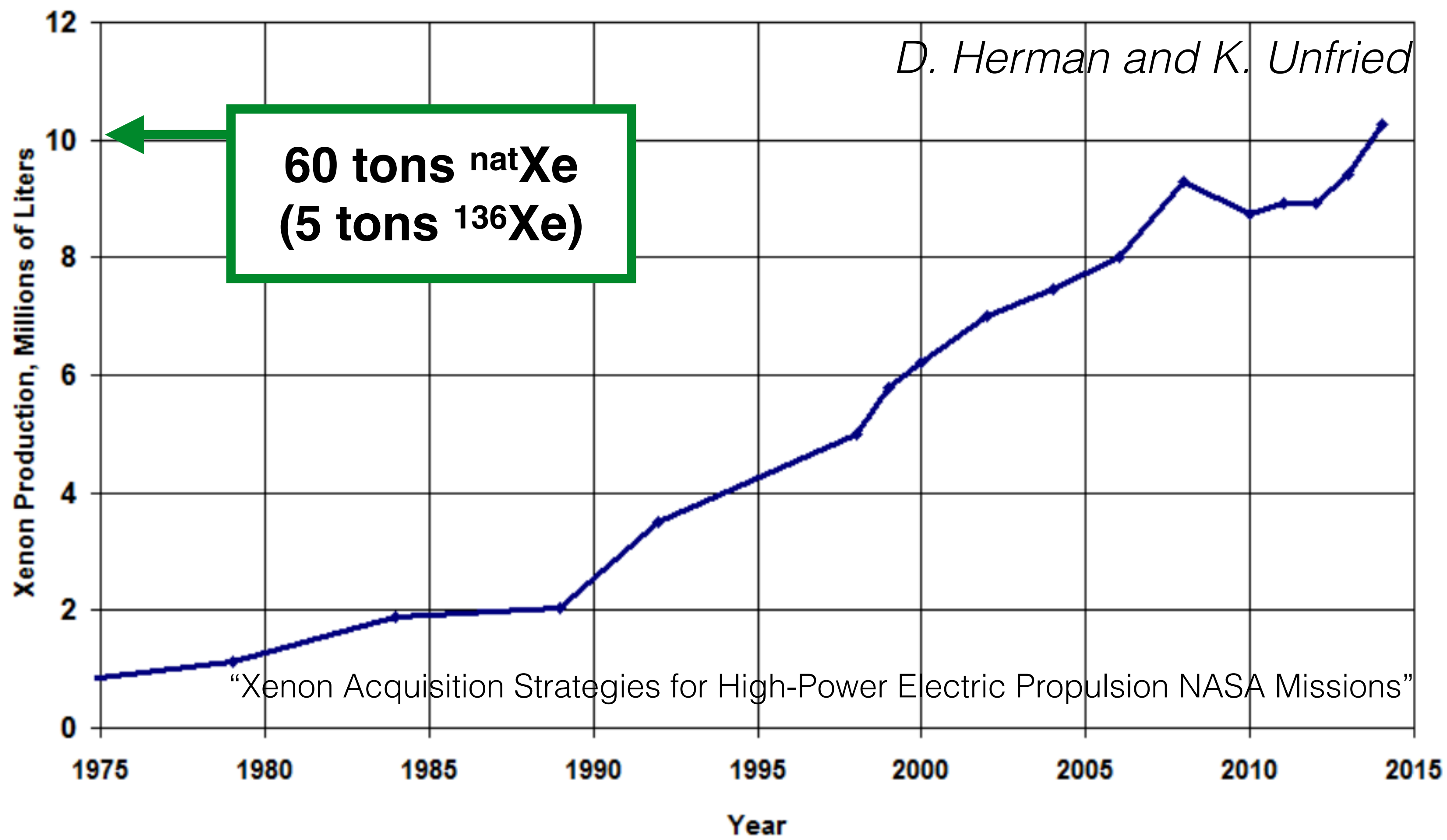
XENON DOPING

What we know:

Xenon doping has been demonstrated at 2%.

Introducing xenon will modify the scintillation profile

Current production of natural Xe is ~60tons per year worldwide. Reliant on expanding Xe extraction and enrichment (currently industry-driven).



Some promising avenues outside HEP:

Metal-organic frameworks have been developed which can efficiently isolate xenon at room temperature

Radioactive waste sites have been found to release large amounts of Xe enriched in ^{136}Xe

Both of these are exciting but will require substantial R&D to move to market

Background Simulation

Backgrounds are simulated using RAT-PAC

We assume a monolithic FD module with nominal materials (not low radioactivity).

Background categories considered:

☠️ Argon-42

☠️ Radioactivity from detector

☠️ Rock radioactivity

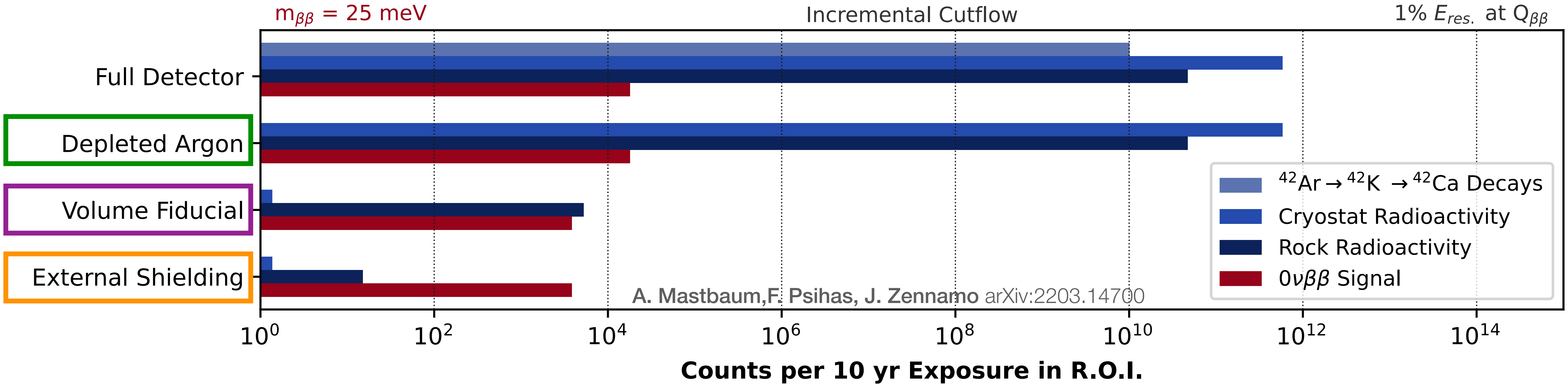
☠️ Environmental neutrons

Cosmogenically-activated radioisotopes

Two-neutrino double beta decay

Solar neutrinos

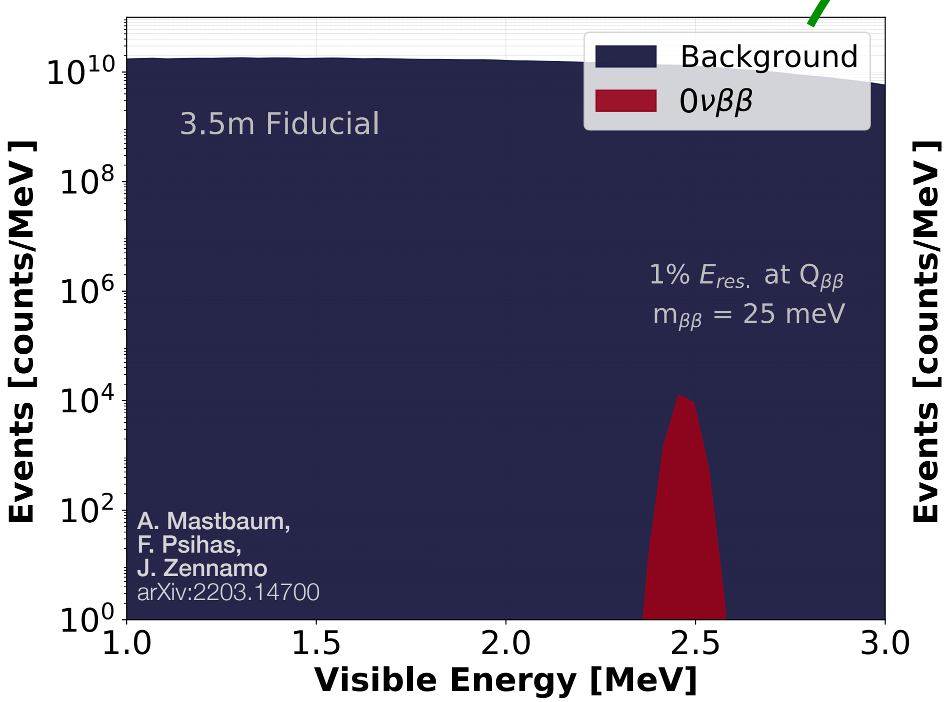
Background Mitigation

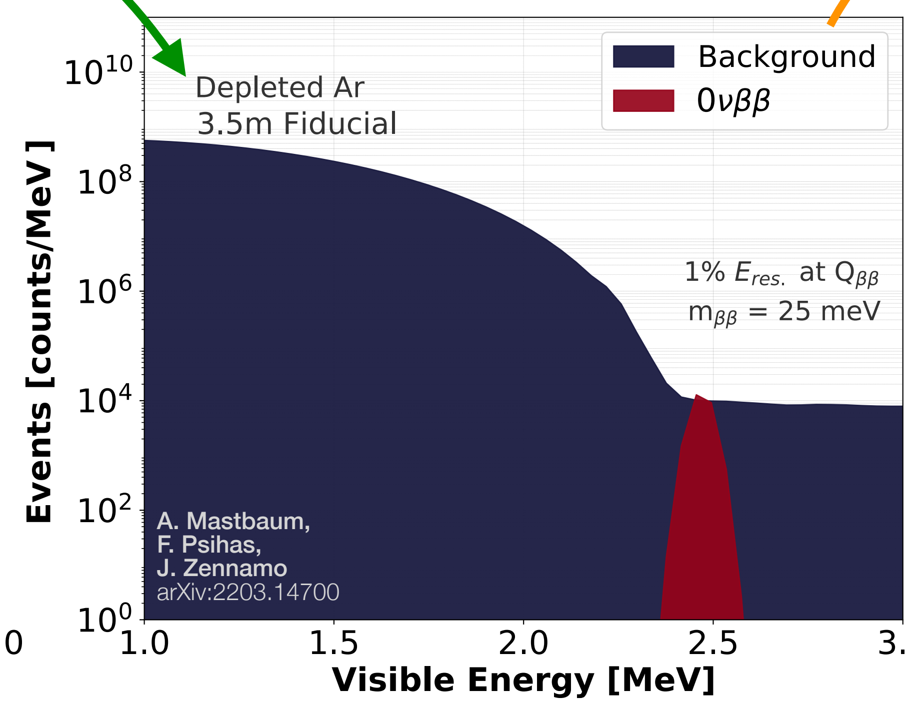


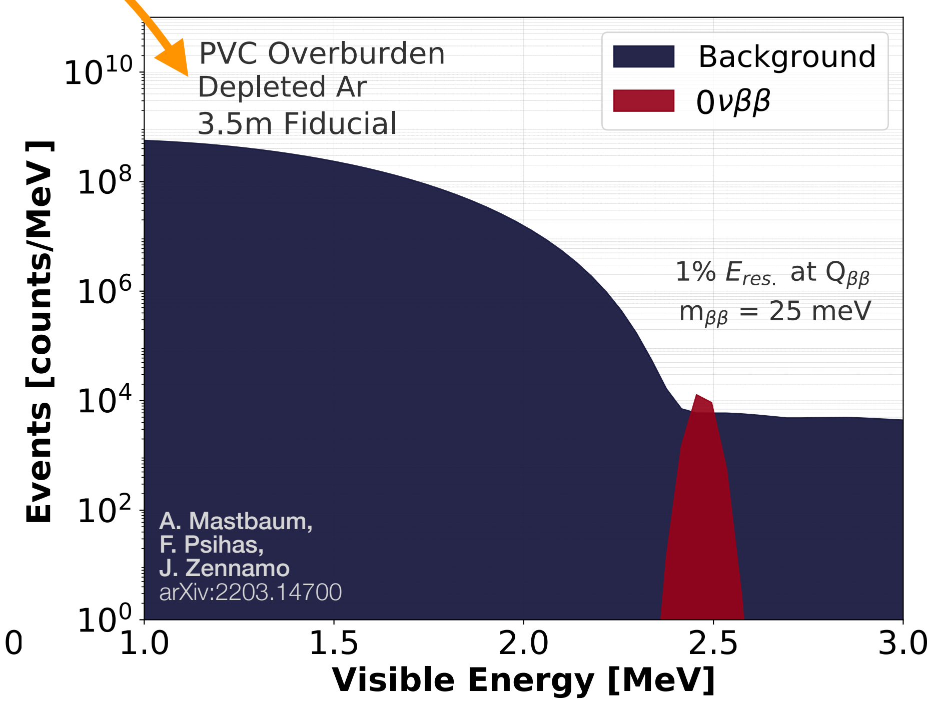
Fiducial Volume

Low-radioactivity argon*

Shielding 1m water equiv.+







*similar to what could enable dark matter searches
E. Church et. al., *JINST* 15 (2020) 09, P09026

+similar for what has been proposed for solar neutrinos
Capozzi, et. al., Phys.Rev.Lett. 123 (2019)

Background Mitigation

Background	Activity	Events in ROI	Mitigation strategy
Isotope Intrinsic			
^{136}Xe, $2\nu\beta\beta$	2%, $T_{1/2} = 2.165 \times 10^{21}$ years [61]	130.28	None
Environmental Radiological Backgrounds			
^{232}Th, Rock	3.34 ppm [8, 52]	46.71	Passive Shielding
^{238}U, Rock	7.11 ppm [8, 52]		Passive Shielding
^{232}Th, Steel	0.1 ppb [50]	117.80	Fiducialization
^{238}U, Steel	1 ppb [50]	2.24	Fiducialization
^{60}Co, Steel	0.013 mBq/g [50]	10.09	Fiducialization
^{39}Ar, LAr	1 Bq/kg [62]	Negligible	Energy threshold
^{222}Rn, LAr	10 mBq/m^3 [8]	Negligible	Coincident ^{214}Po Tag
^{42}Ar, LAr	Negligible [63]	Negligible	Use of ^{42}Ar depleted LAr
Solar Neutrinos			
^{8}B ν Elastic Scatters	Standard Solar Model Flux [64]	662.04	
^{8}B ν_e Charged Current	Standard Solar Model Flux [64]	196.00	Photon Coincidence Tag
Spallation Products			
^{32}P	34 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Photon Coincidence Tag
^{39}Cl	150 day^{-1}(10 kton)$^{-1}$ [59]	14.59	Coincident Muon Timing
^{41}Ar	1600 day^{-1}(10 kton)$^{-1}$ [59]	6.54	Photon Coincidence Tag
^{137}Xe	3.8 day^{-1}(10 kton)$^{-1}$ [65]	449.43	Photon Coincidence Tag
^{16}N	0.033 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing
^{30}Al	1.4 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing
^{40}Cl	27 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing
^{20}F	2 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing
^{34}P	12 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing
^{38}Cl	110 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	None
^{36}Cl	110 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	None
^{37}Ar	110 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Photon Coincidence Tag
^{33}P	34 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Photon Coincidence Tag
^{11}Be	0.34 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing

arxiv 2203.10147

Demonstrated the feasibility of reconstructing the MeV-scale signal 214Bi-214Po topology in a large-scale wire-readout LArTPC

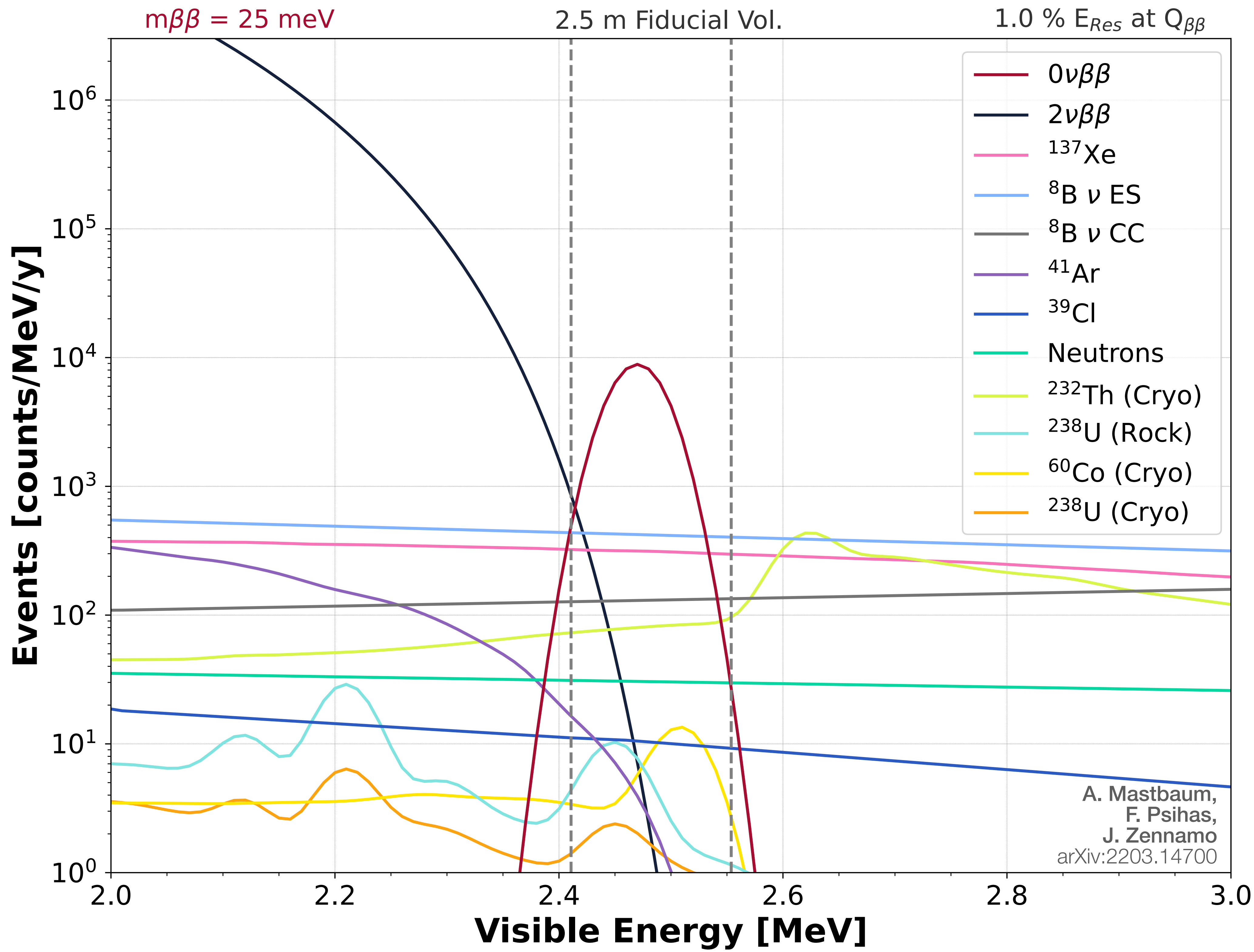
Veto photon coincidence within 32 cm of signal candidates

Veto window within 2m and 60sec of all muon tracks.

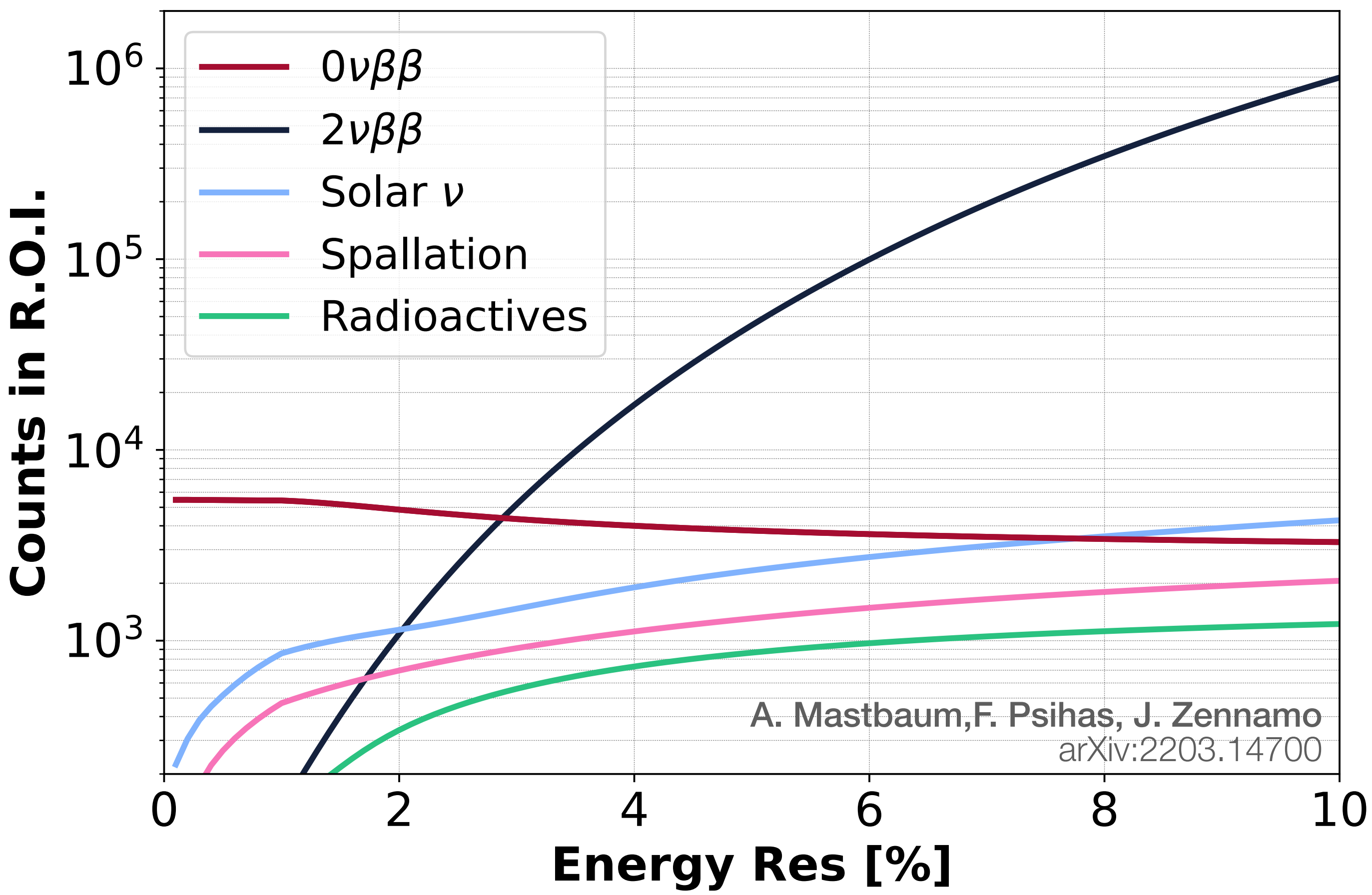
Background Mitigation

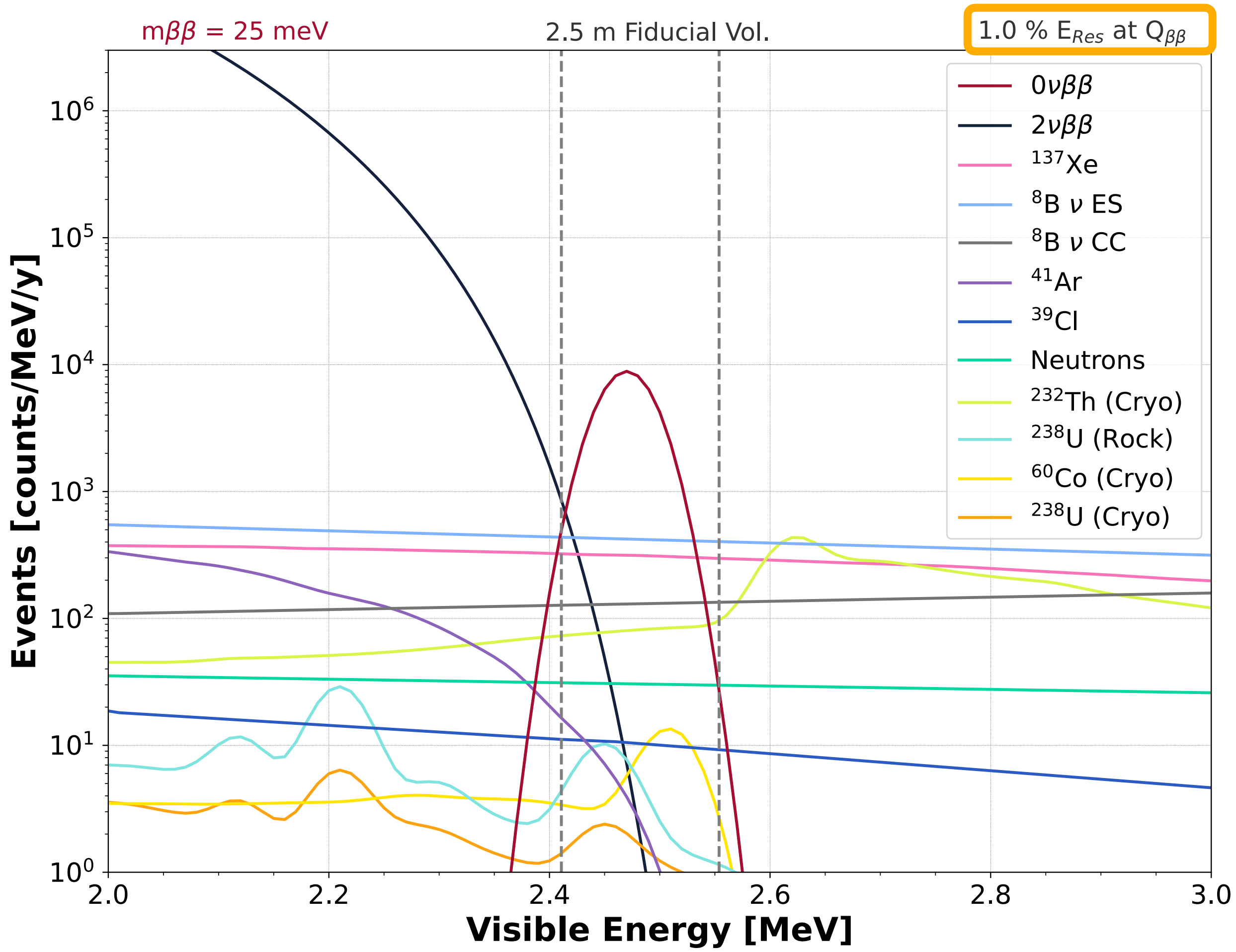
Background	Activity	Events in ROI	Mitigation strategy	
Isotope Intrinsic				
^{136}Xe, $2\nu\beta\beta$	2%, $T_{1/2} = 2.165 \times 10^{21}$ years [61]	130.28	None	2νββ
Environmental Radiological Backgrounds				
^{232}Th, Rock	3.34 ppm [8, 52]	46.71	Passive Shielding	
^{238}U, Rock	7.11 ppm [8, 52]		Passive Shielding	
^{232}Th, Steel	0.1 ppb [50]	117.80	Fiducialization	Radioactivity
^{238}U, Steel	1 ppb [50]	2.24	Fiducialization	
^{60}Co, Steel	0.013 mBq/g [50]	10.09	Fiducialization	
^{39}Ar, LAr	1 Bq/kg [62]	Negligible	Energy threshold	
^{222}Rn, LAr	10 mBq/m^3 [8]	Negligible	Coincident ^{214}Po Tag	
^{42}Ar, LAr	Negligible [63]	Negligible	Use of ^{42}Ar depleted LAr	
Solar Neutrinos				
^{8}B ν Elastic Scatters	Standard Solar Model Flux [64]	662.04		Solar
^{8}B ν_e Charged Current	Standard Solar Model Flux [64]	196.00	Photon Coincidence Tag	
Spallation Products				
^{32}P	34 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Photon Coincidence Tag	
^{39}Cl	150 day^{-1}(10 kton)$^{-1}$ [59]	14.59	Coincident Muon Timing	
^{41}Ar	1600 day^{-1}(10 kton)$^{-1}$ [59]	6.54	Photon Coincidence Tag	Spallation
^{137}Xe	3.8 day^{-1}(10 kton)$^{-1}$ [65]	449.43	Photon Coincidence Tag	
^{16}N	0.033 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing	
^{30}Al	1.4 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing	
^{40}Cl	27 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing	
^{20}F	2 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing	
^{34}P	12 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing	
^{38}Cl	110 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	None	
^{36}Cl	110 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	None	
^{37}Ar	110 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Photon Coincidence Tag	
^{33}P	34 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Photon Coincidence Tag	
^{11}Be	0.34 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing	

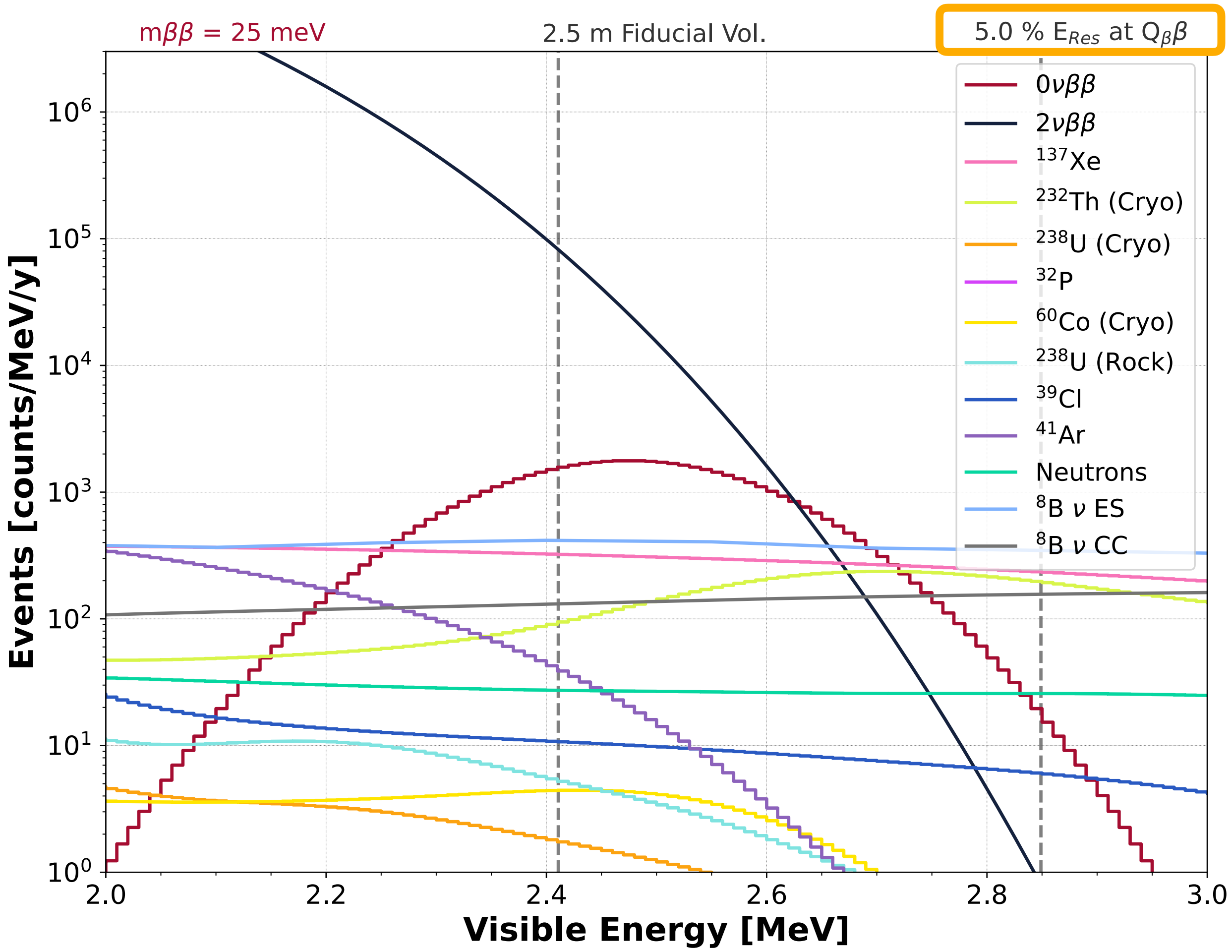
BACKGROUNDS HONORABLE MENTIONS



BACKGROUNDS
AND ENERGY RESOLUTION







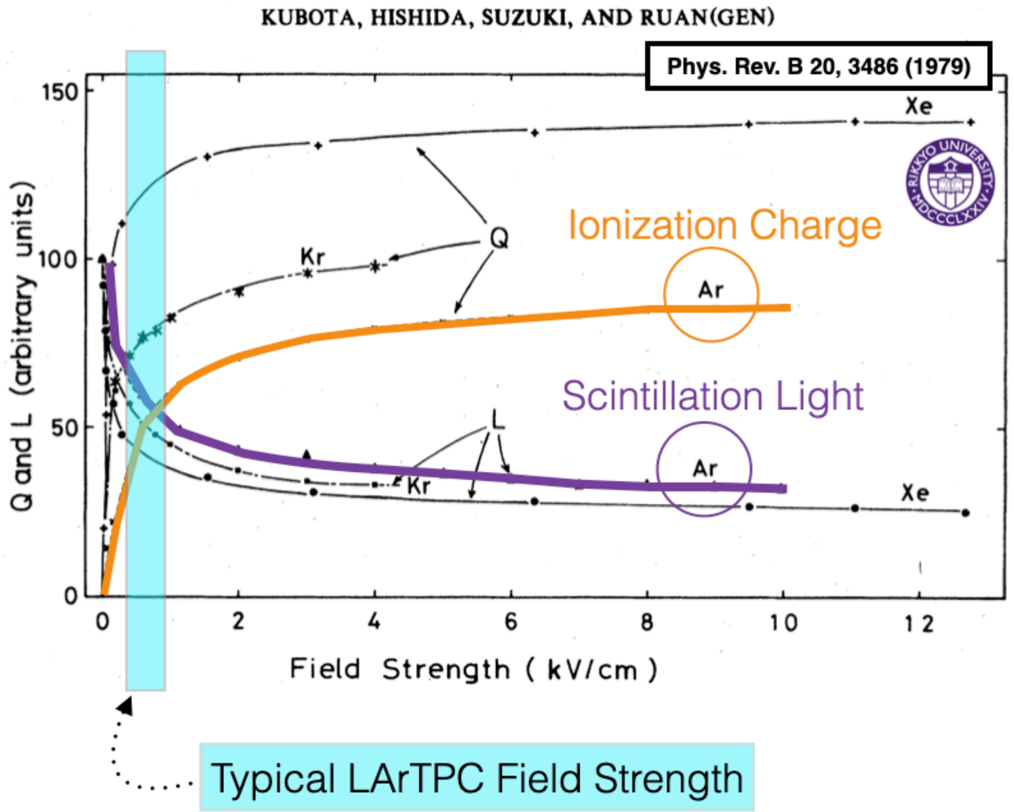
Energy resolution is a crucial component of this concept.

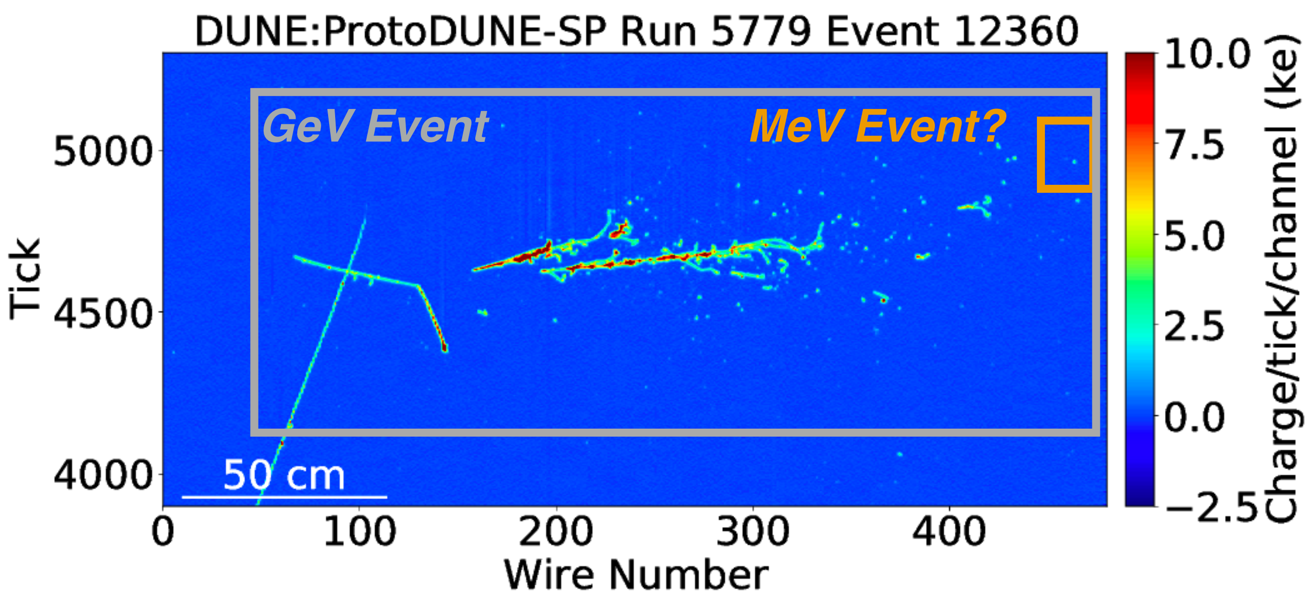
$E_{res} < 3\%$ is essential to reduce the 2vββ background.

Charge + Light

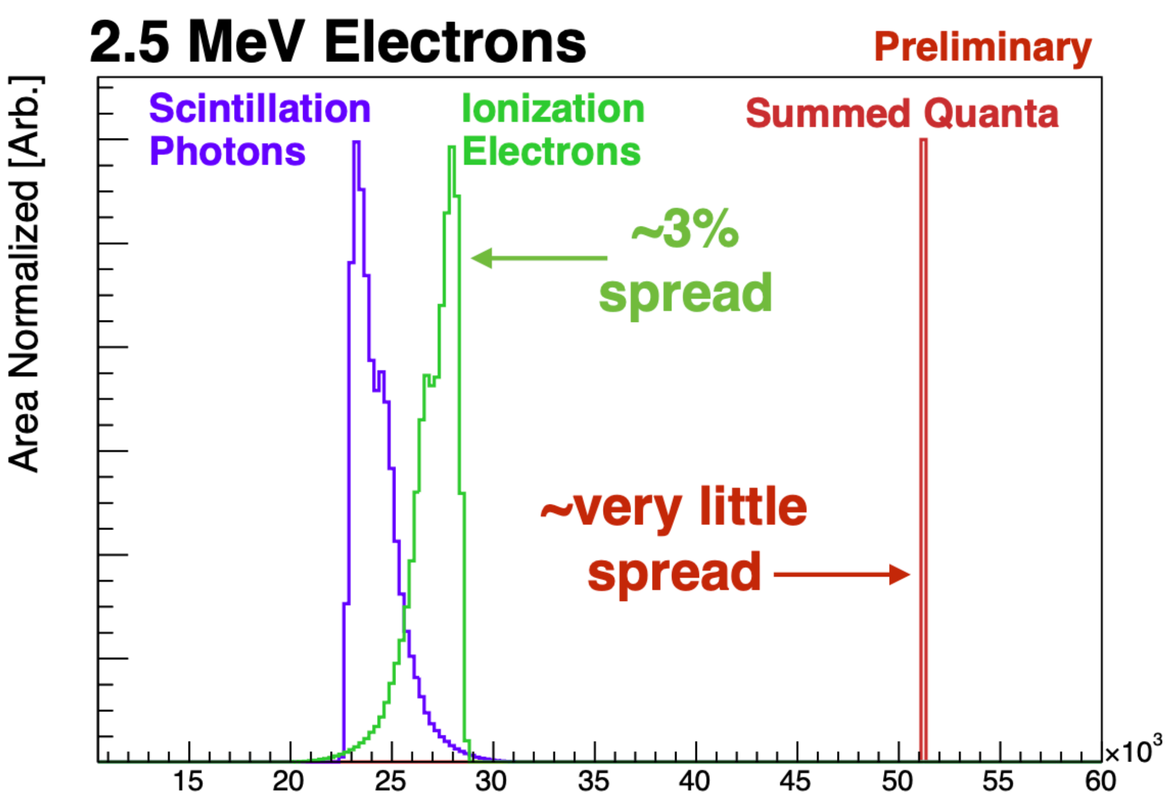
Charge + Light = Constant

On DUNE, we'll expect ~50/50 **charge** to **light** breakdown.





JINST 15 (2020) P12004
ProtoDUNE-SP

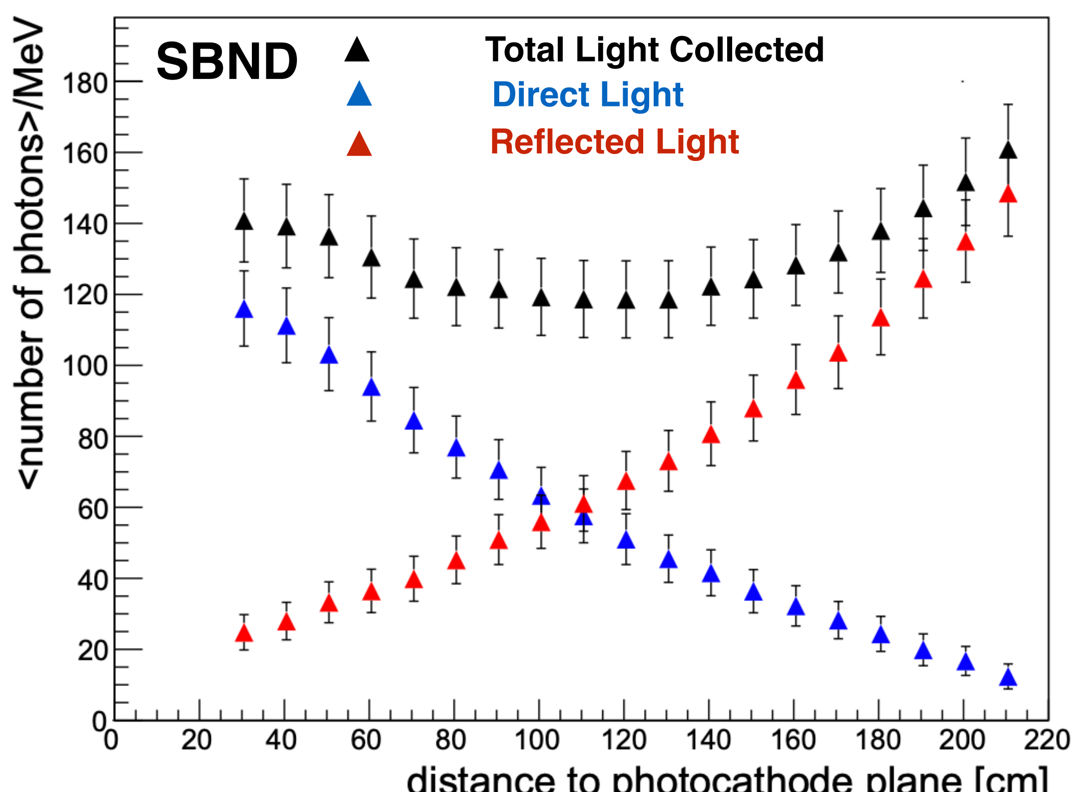


ENERGY RESOLUTION

Combining charge and light signals is necessary for precise energy resolution.

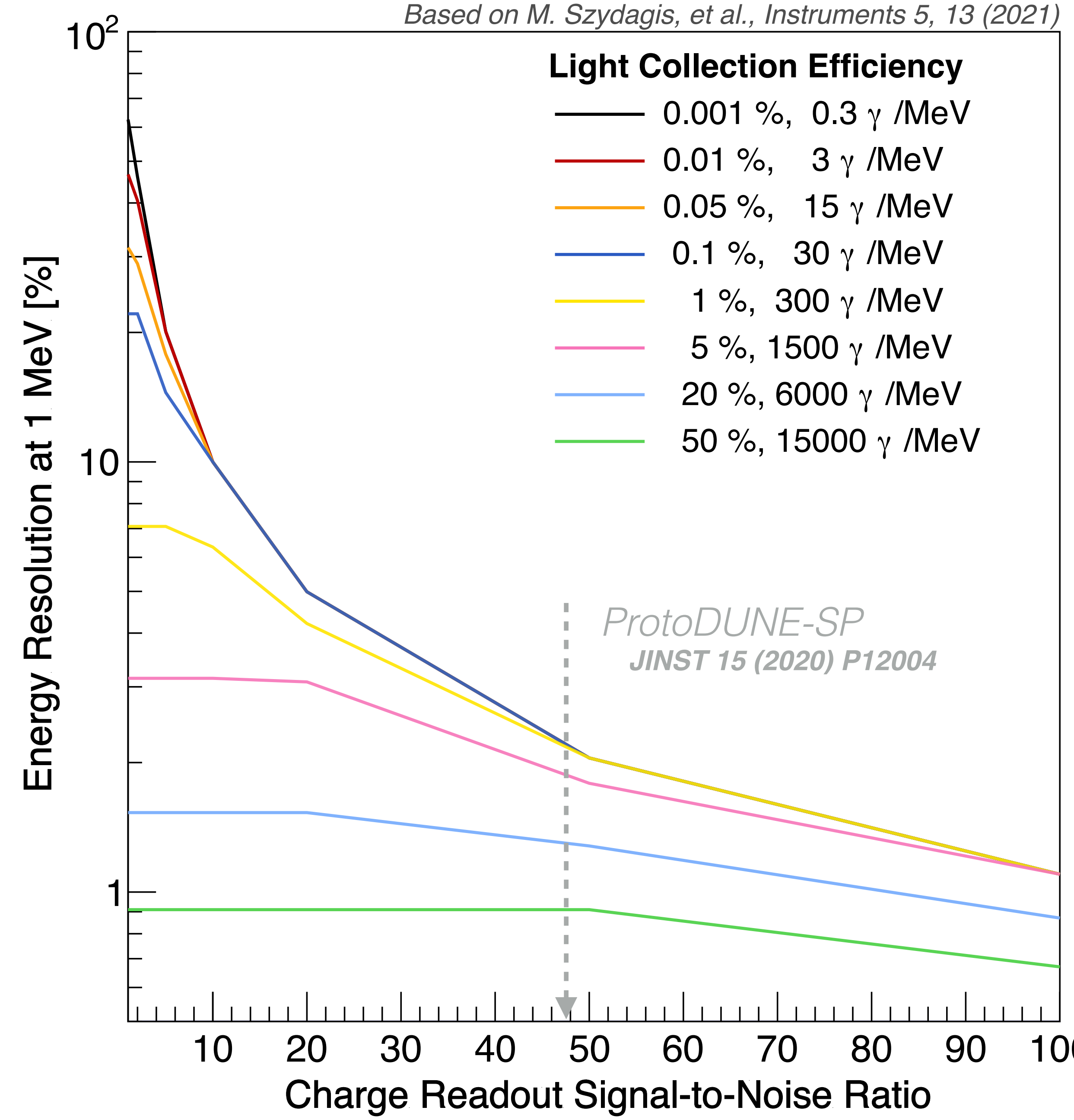
We need > 20% light collection efficiency, which is beyond the current capabilities FD1 and FD2

We propose **using photosensitive dopants** to utilize the high charge collection efficiency of LArTPCs



D. Garcia-Gamez
Journal of Physics: Conf. Series 888 (2017) 012094

Based on M. Szydagis, et al., Instruments 5, 13 (2021)



R&D Requirements

Finding optimal doping strategy

Understanding timing and triggering in a light-less LAr module

Photosensitive Dopants

The most commonly used have ionization energies of 7-9 eV:
Tetramethylgermane (**TMG**), $(CH_3)_4Ge$,
Trimethylamine (**TMA**), $N(CH_3)_3$,
Triethylamine (**TEA**), $N(CH_2CH_3)_3$

Small test stands in the 80s explored a variety of chemicals and found an increase in charge for highly scintillating particles

Using 5.5 MeV α-source found that **TMG** increase

Implies 10,000 photons/MeV for MeV-scale electron signals

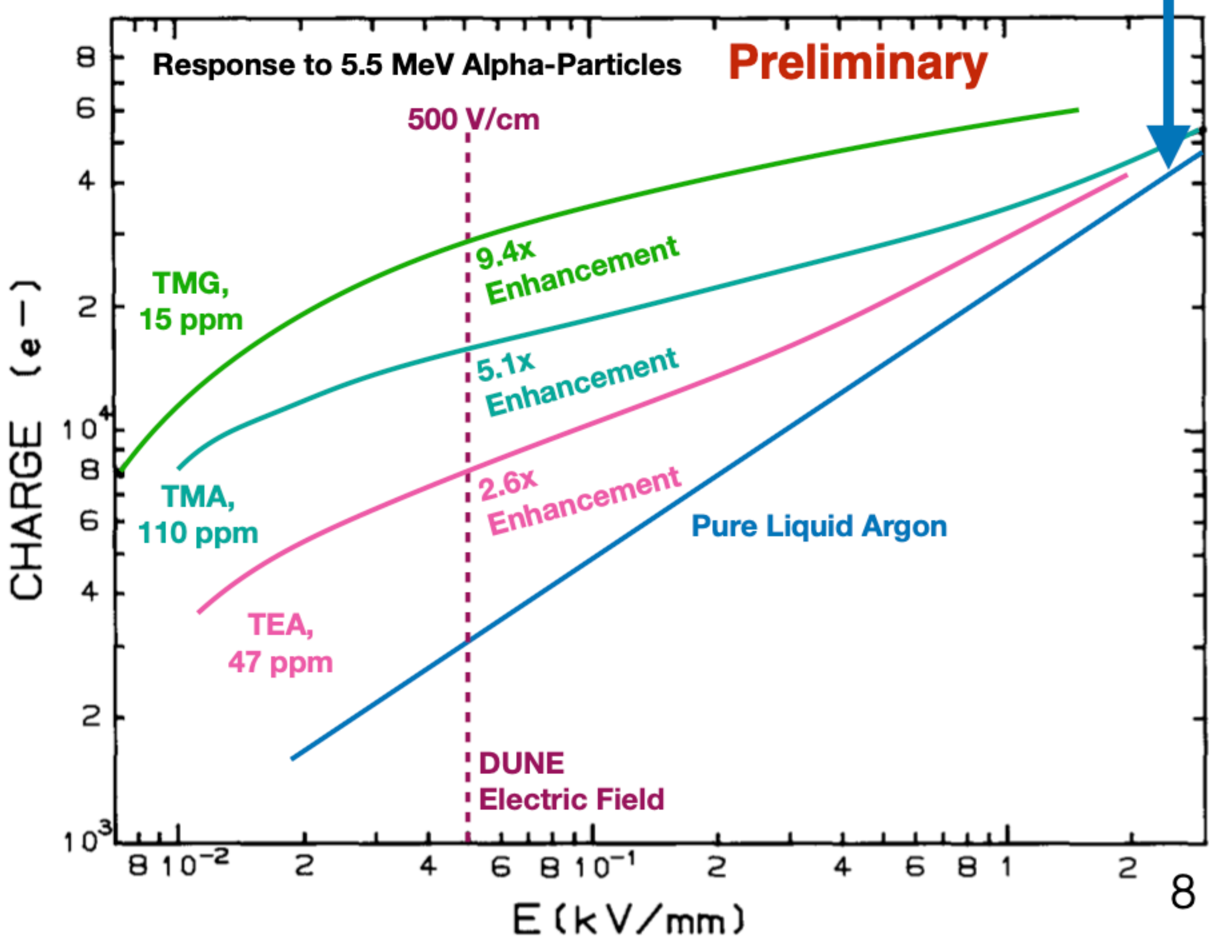
<u>Ionization Energies</u>

TMG	9.2 eV
TMA	7.8 eV
TEA	7.5 eV

(In LAr these drop by ~0.7 eV)

<u>Pure LAr @ 276 V/cm</u>

Courtesy of Ivan Lepetic

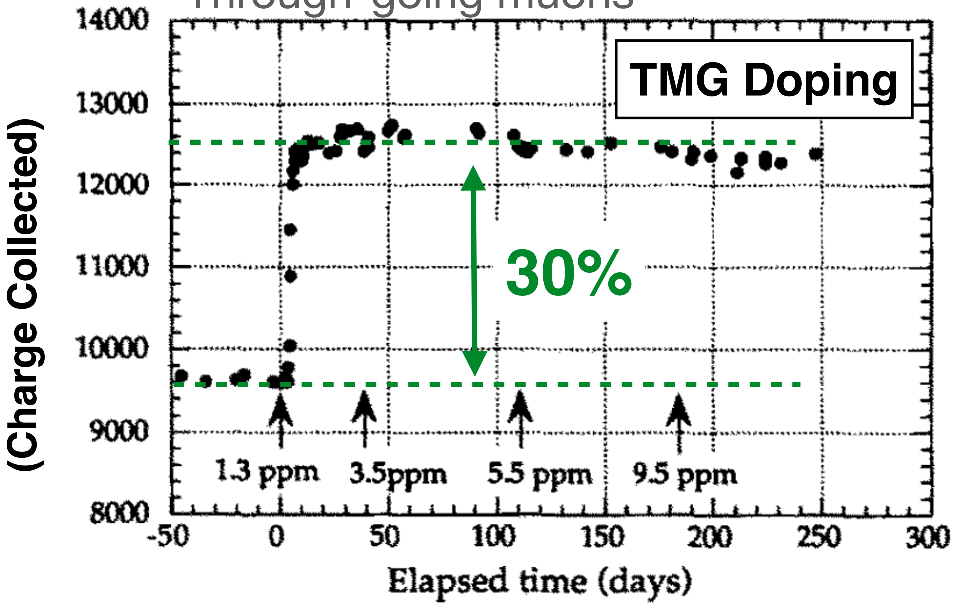


EFFECTS OF PHOTOSENSITIVE DOPANTS

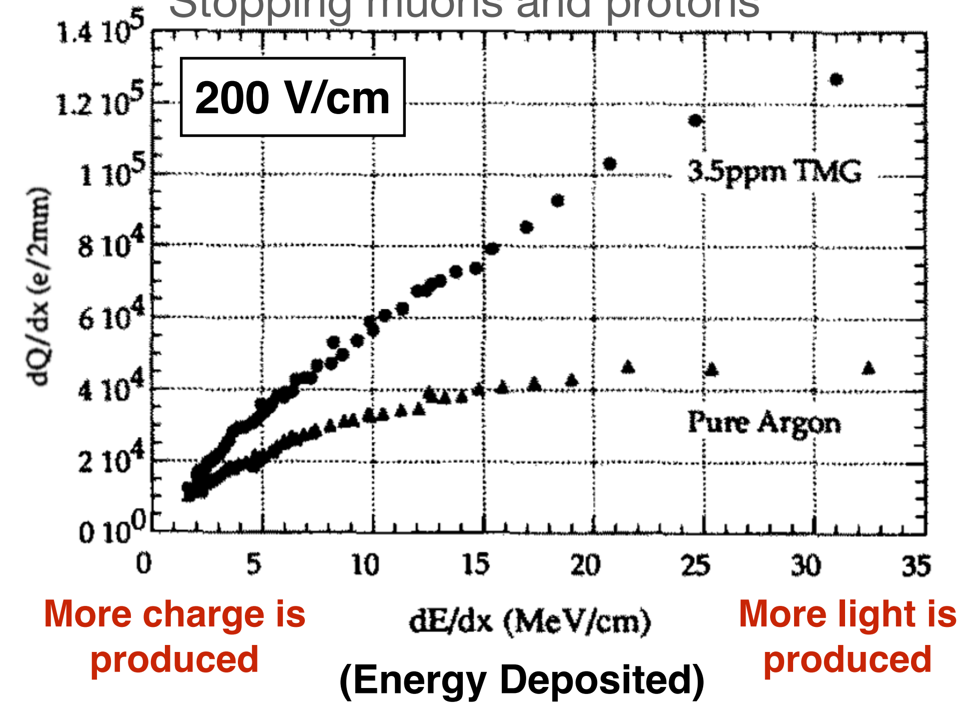
Studies with alpha particles show that we can expect up to 60% light collection equivalent

Nucl. Instrum. Methods. Phys. Res. B 355, 660 (1995).
ICARUS Collaboration

Through-going muons



Stopping muons and protons

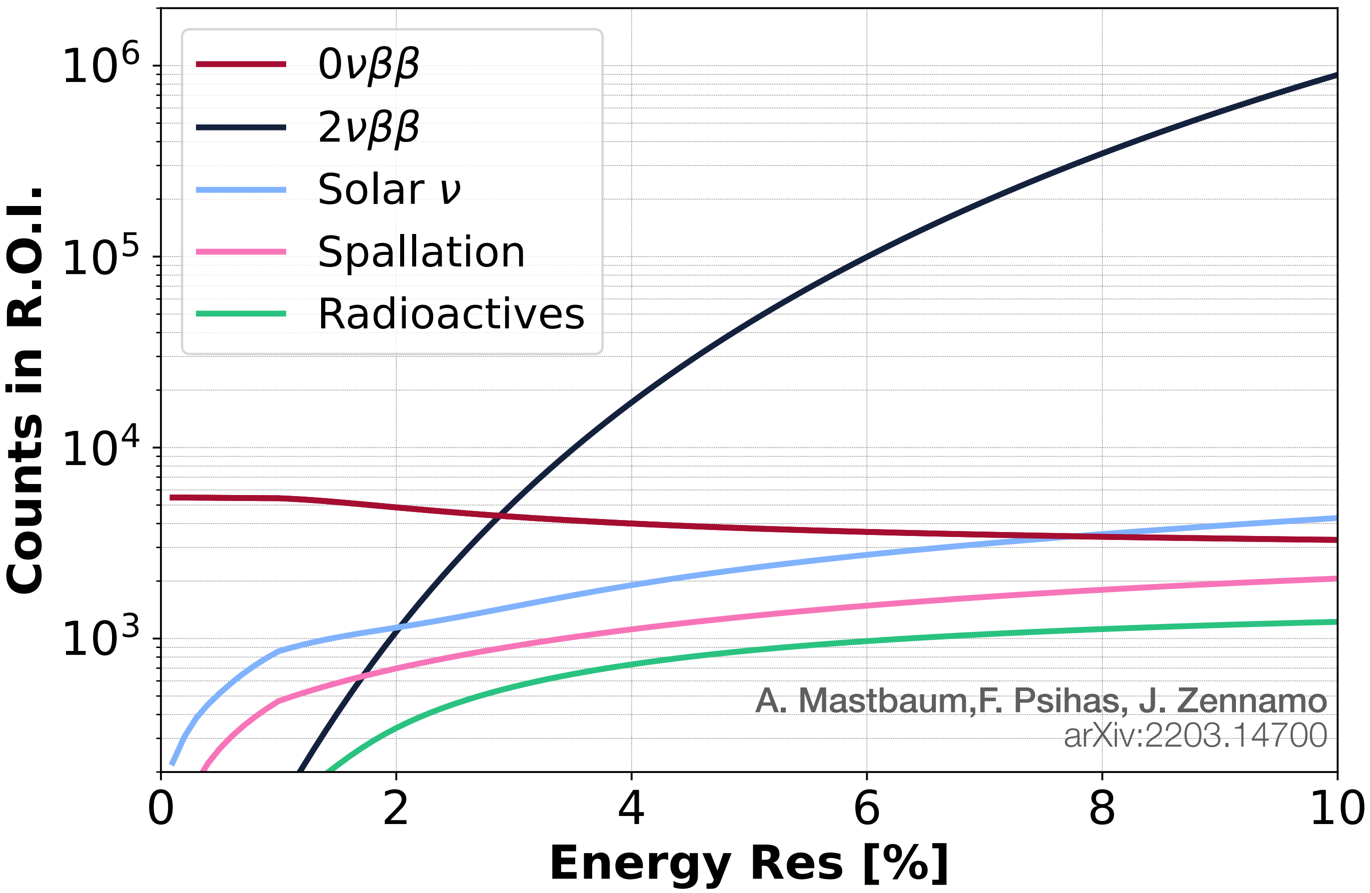


Effects on the existing low-E physics program

- More linear detector response
- Lower thresholds
- Better resolution for highly scintillating particles like alphas and nuclear recoils
- Better resolution of low energy hadronic energy components

Requirements

Energy resolution is a crucial component of this concept. **E_{res} < 3%** is essential to reduce the 2νββ background.



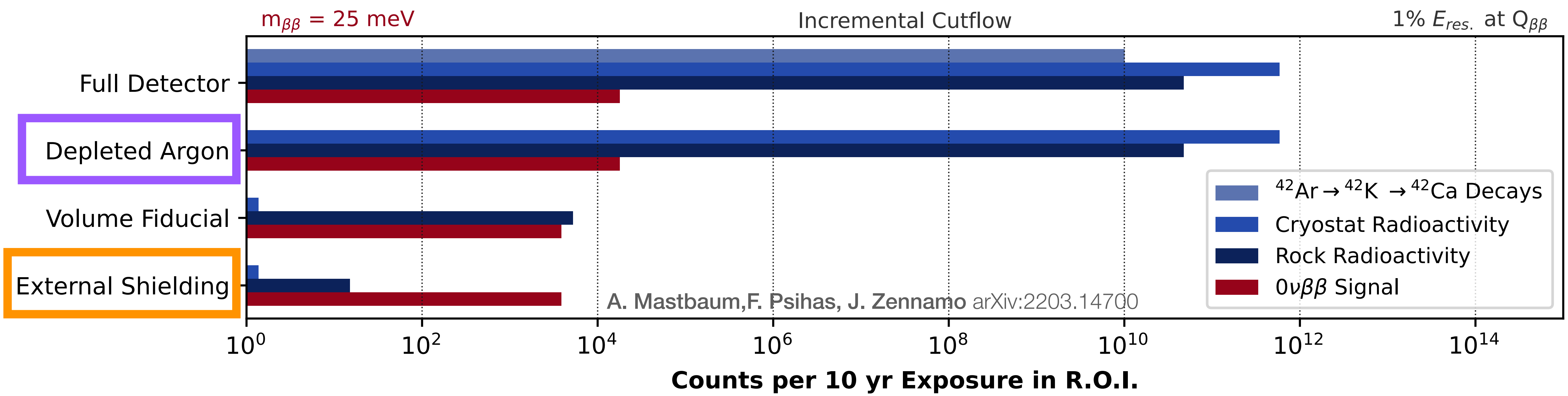
Radioactivity assumed for a monolithic detector with nominal materials (not low radioactivity)

Low-radioactivity argon*

*similar to what could enable dark matter searches
E. Church et. al., *JINST* 15 (2020) 09, P09026

Shielding 1m water equiv.+

+similar for what has been proposed for solar neutrinos
Capozzi, et. al., Phys.Rev.Lett. 123 (2019)



"REQUIREMENTS"

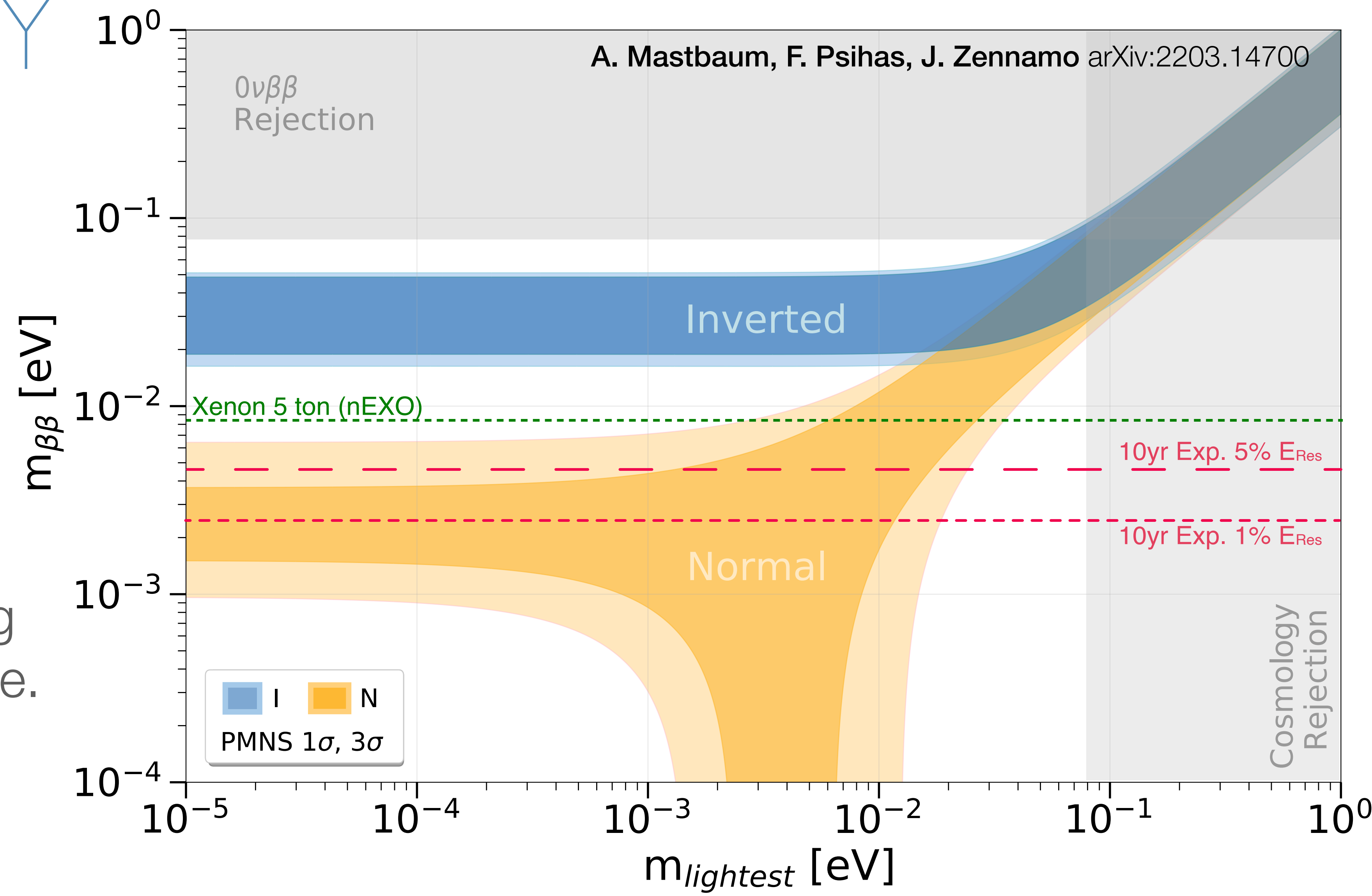
⚖️ **There is room for adjustment**
💡 **AN idea (others might work)**
❗ **Hard requirement**

- ⚖️ Xenon doping at 2%
- 💡 Monolithic LAr TPC
- ❗ Depleted argon
- ⚖️ External shielding
- ⚖️ <3% energy resolution
- 💡 Photosensitive dopants

0νββ SENSITIVITY

We perform a counting analysis with 2% 136Xe, 10 year exposure, and 1% energy resolution, DUNE-β.

There is room for modifying this base-concept while still attaining sensitivities in the 2-4 meV range.

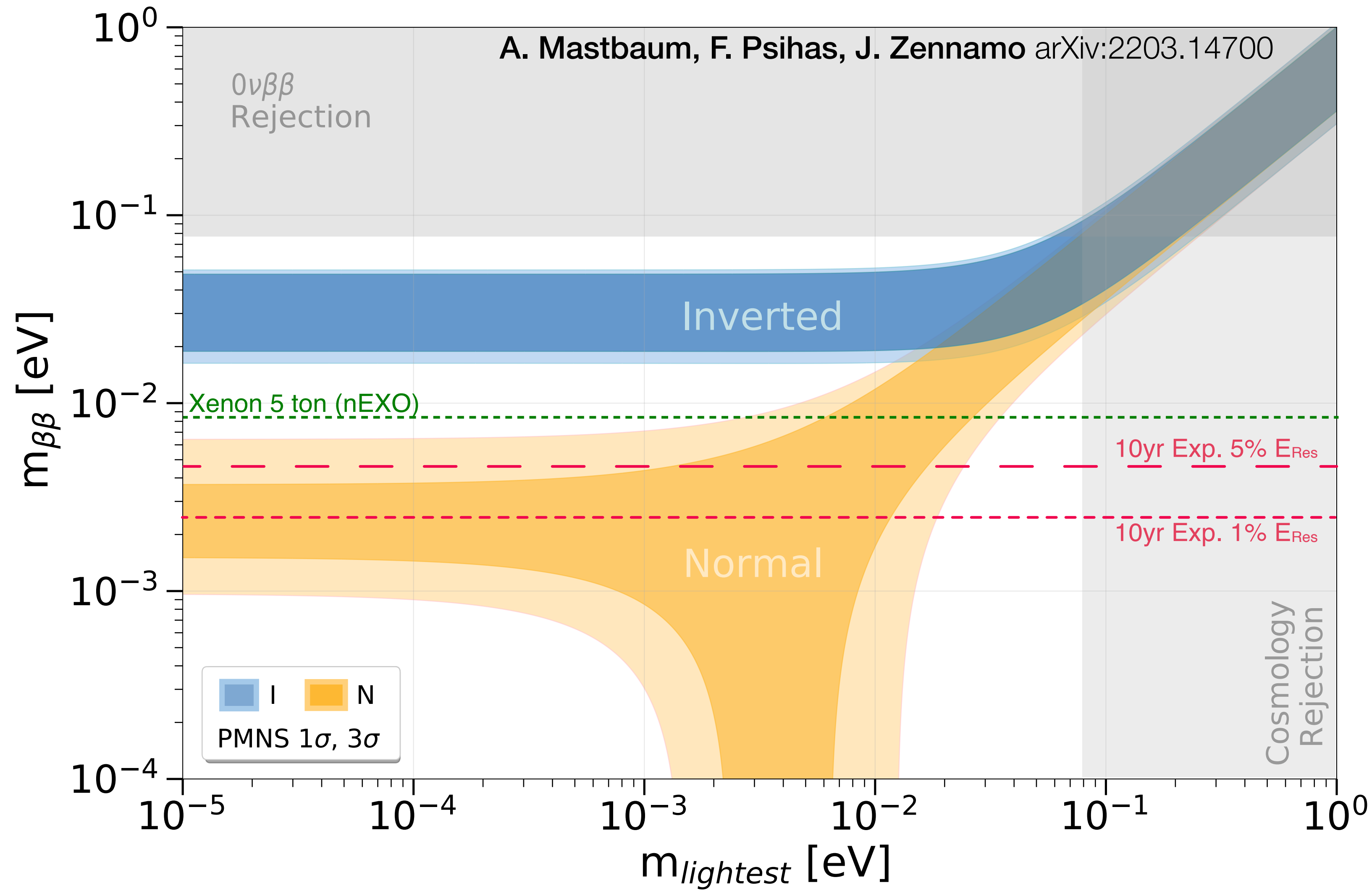


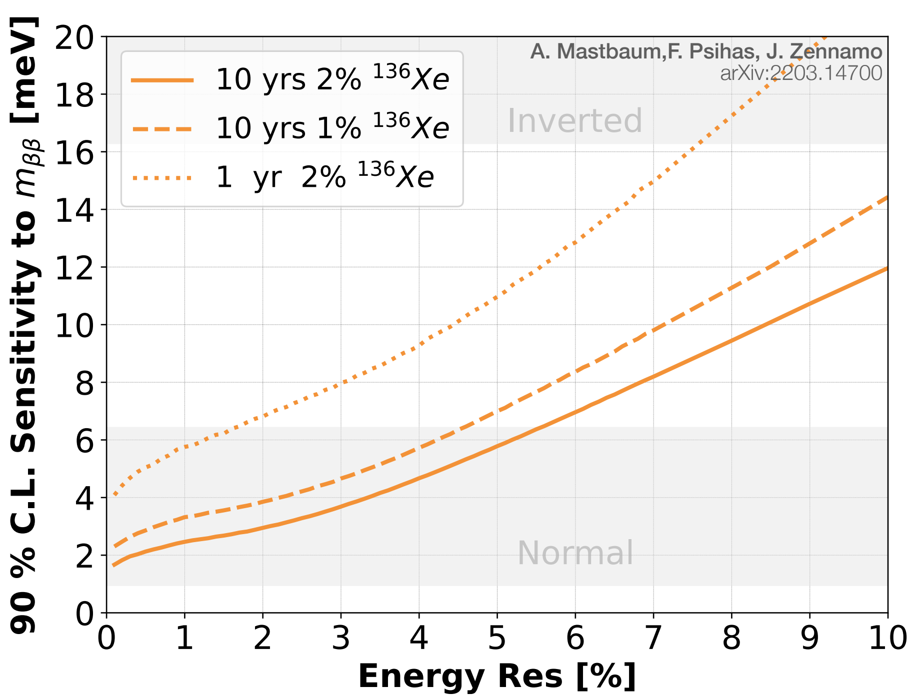
SUMMARY

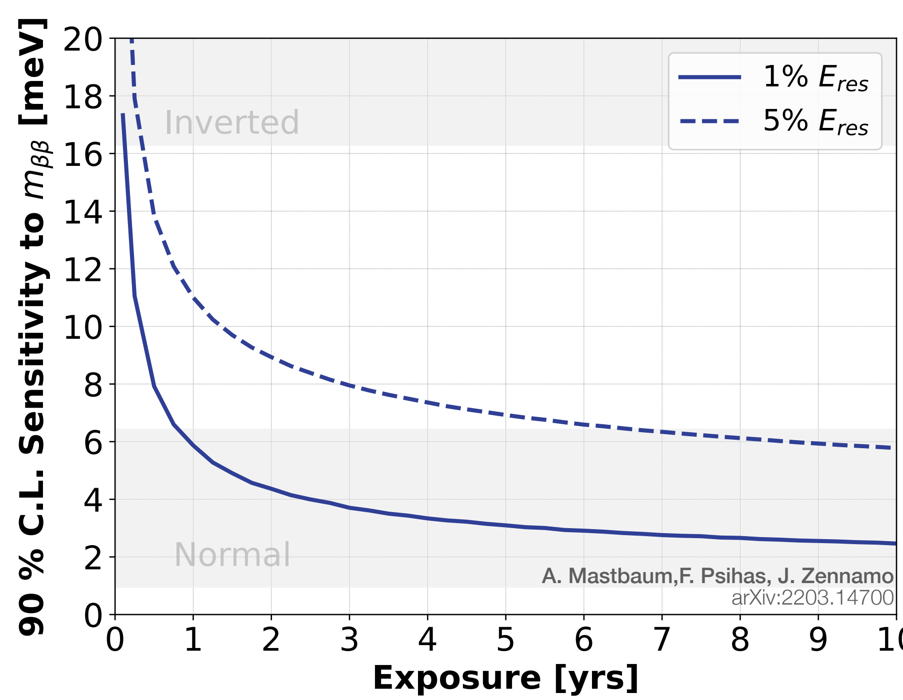
This doping concept could extend DUNE's physics program with sensitivities to 0νββ decay as low as mββ ~ 2meV.

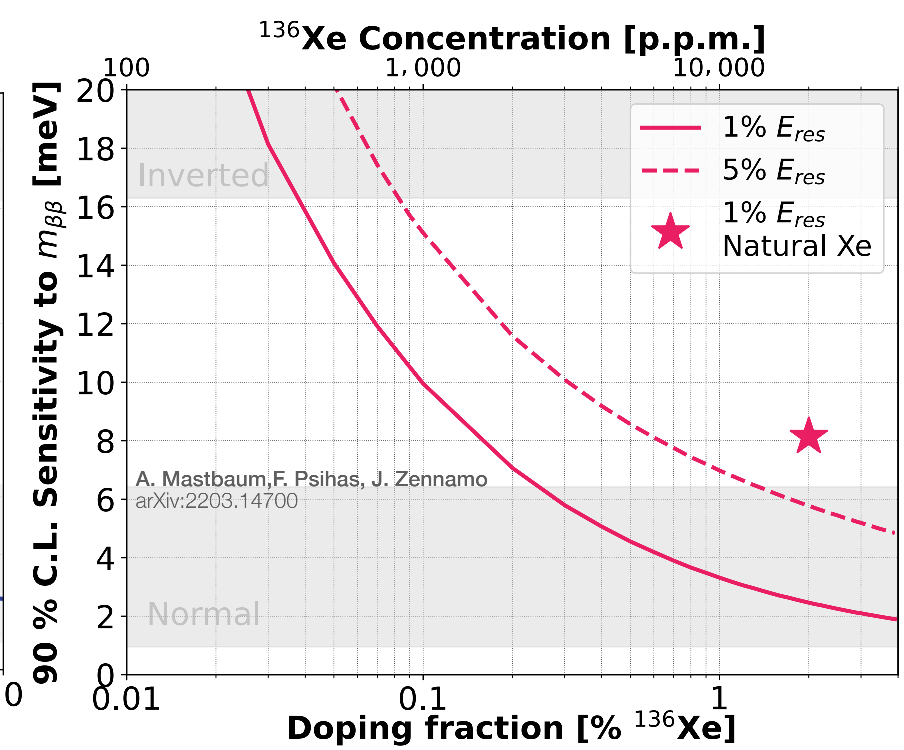
This concept employs Xe-doping, photo-sensitive dopants, depleted argon, and an external shielding compatible with other low energy physics concepts for DUNE phase-II.

The required modifications open a rich R&D program in which will enhance our low energy capabilities in LArTPCs









Backup

These are not the slides you're looking for

Photosensitive Dopants

The most commonly used have ionization energies of 7-9 eV: Tetramethylgermane (**TMG**), $(CH_3)_4Ge$, Trimethylamine (**TMA**), $N(CH_3)_3$, Triethylamine (**TEA**), $N(CH_2CH_3)_3$

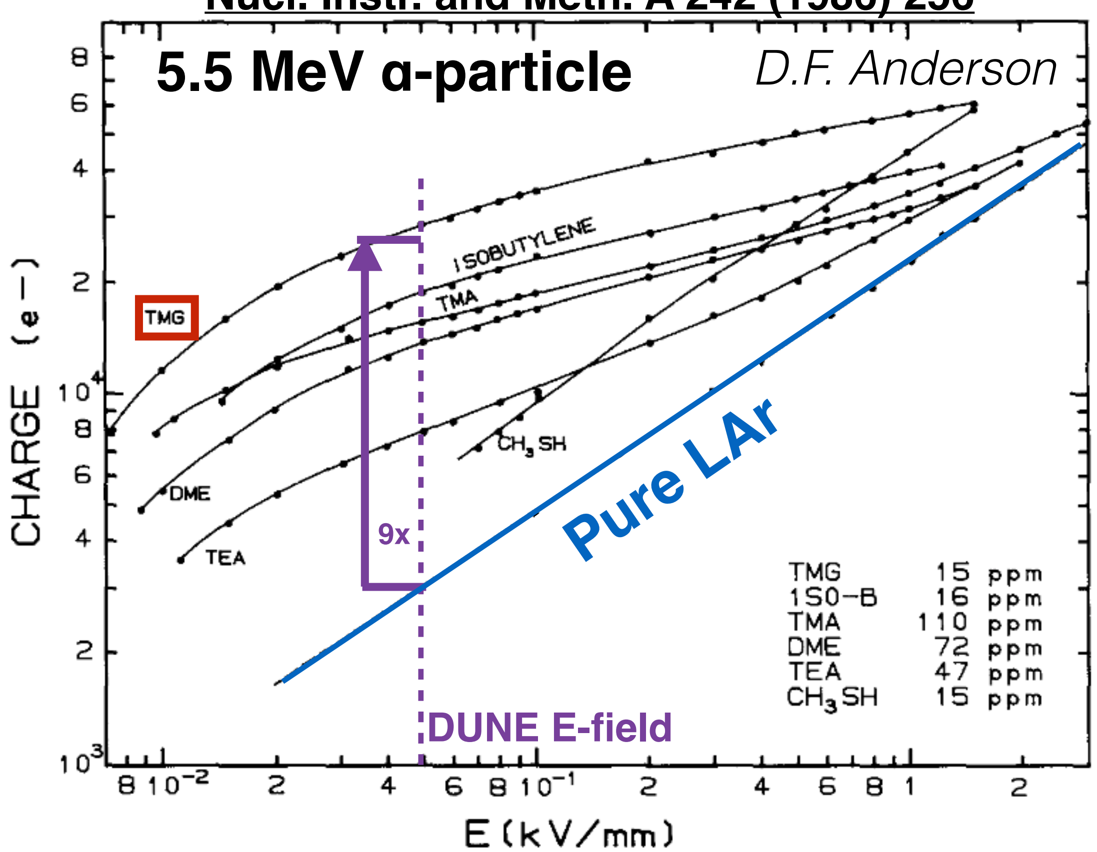
Small test stands explored a variety of chemicals and found an increase in charge for highly scintillating particles

Implies 10,000 photons/MeV for MeV-scale electron signals

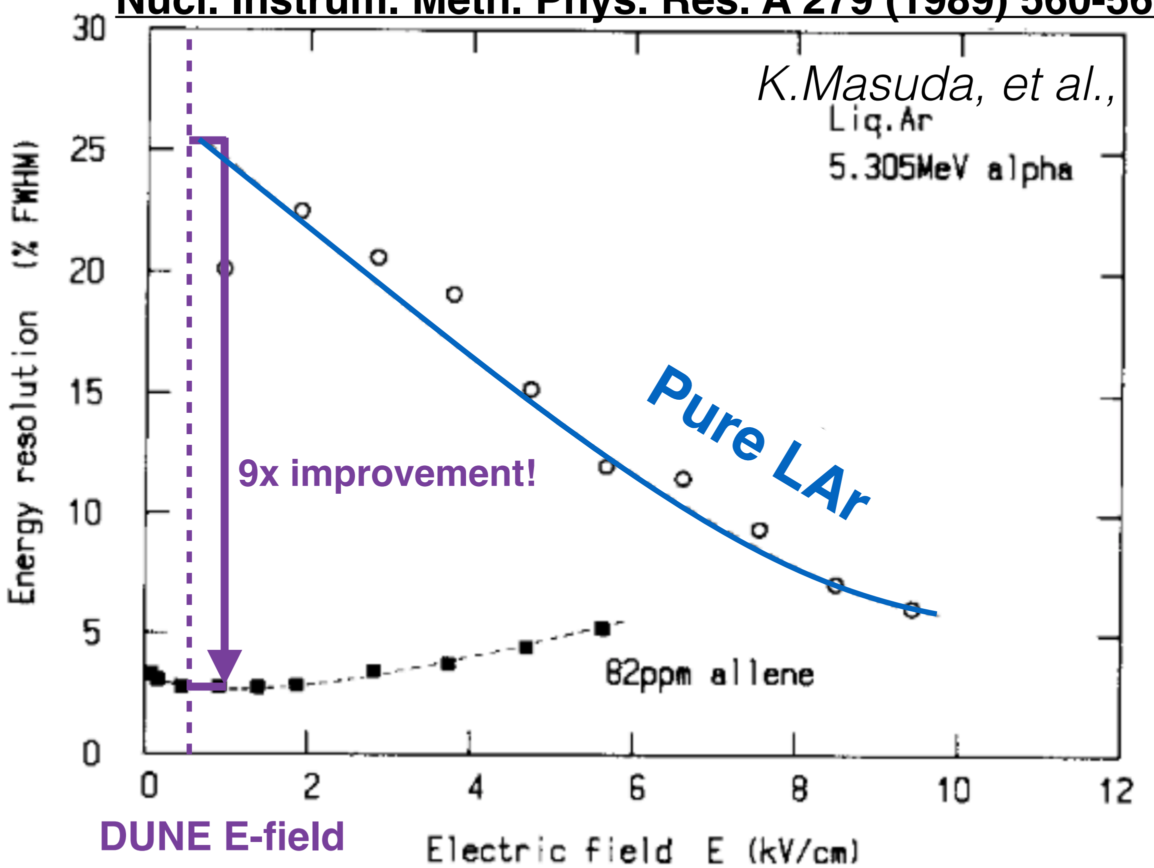
Simulated Event in Pure LAr

Courtesy of Ivan Lepetic

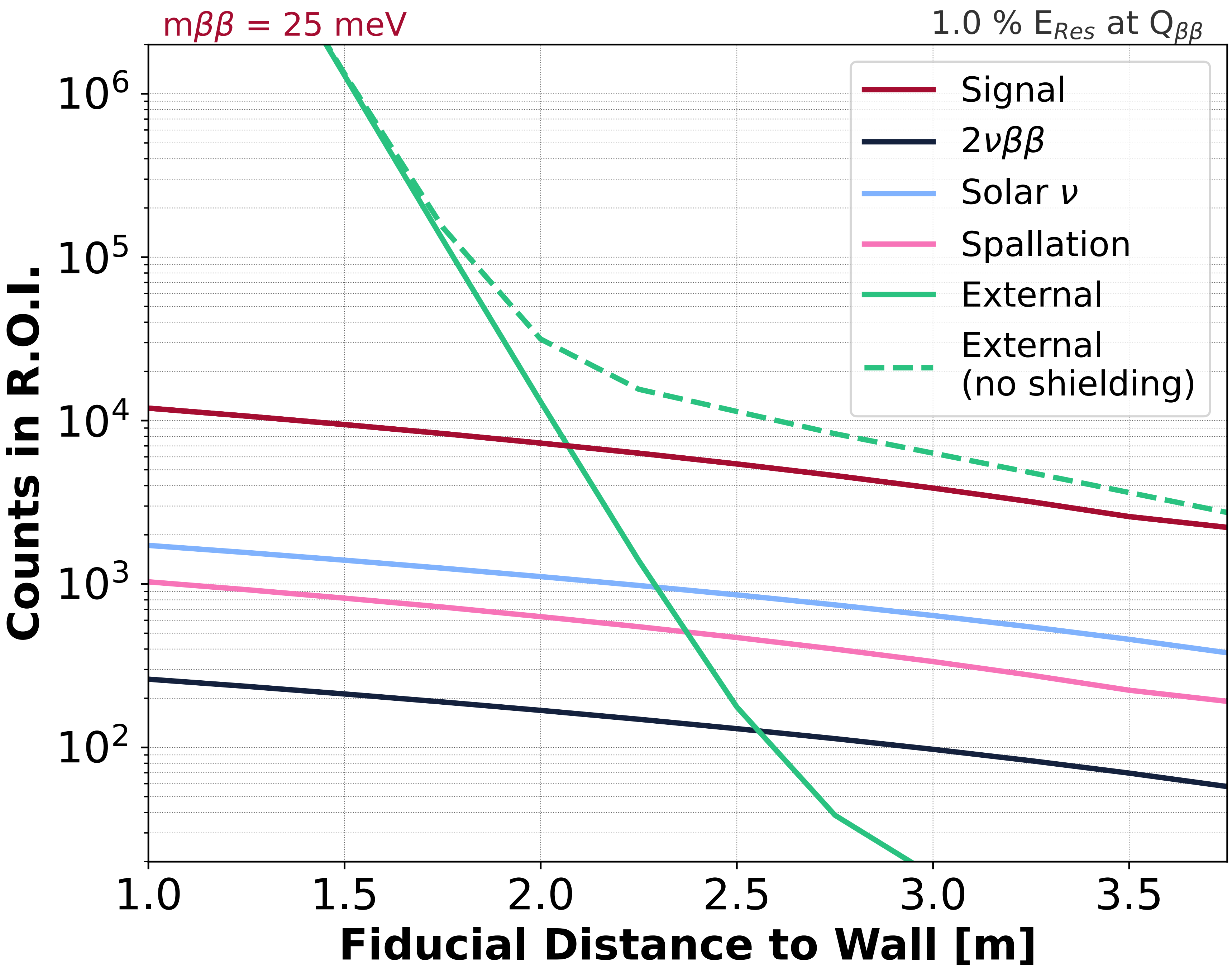
Nucl. Instr. and Meth. A 242 (1986) 256



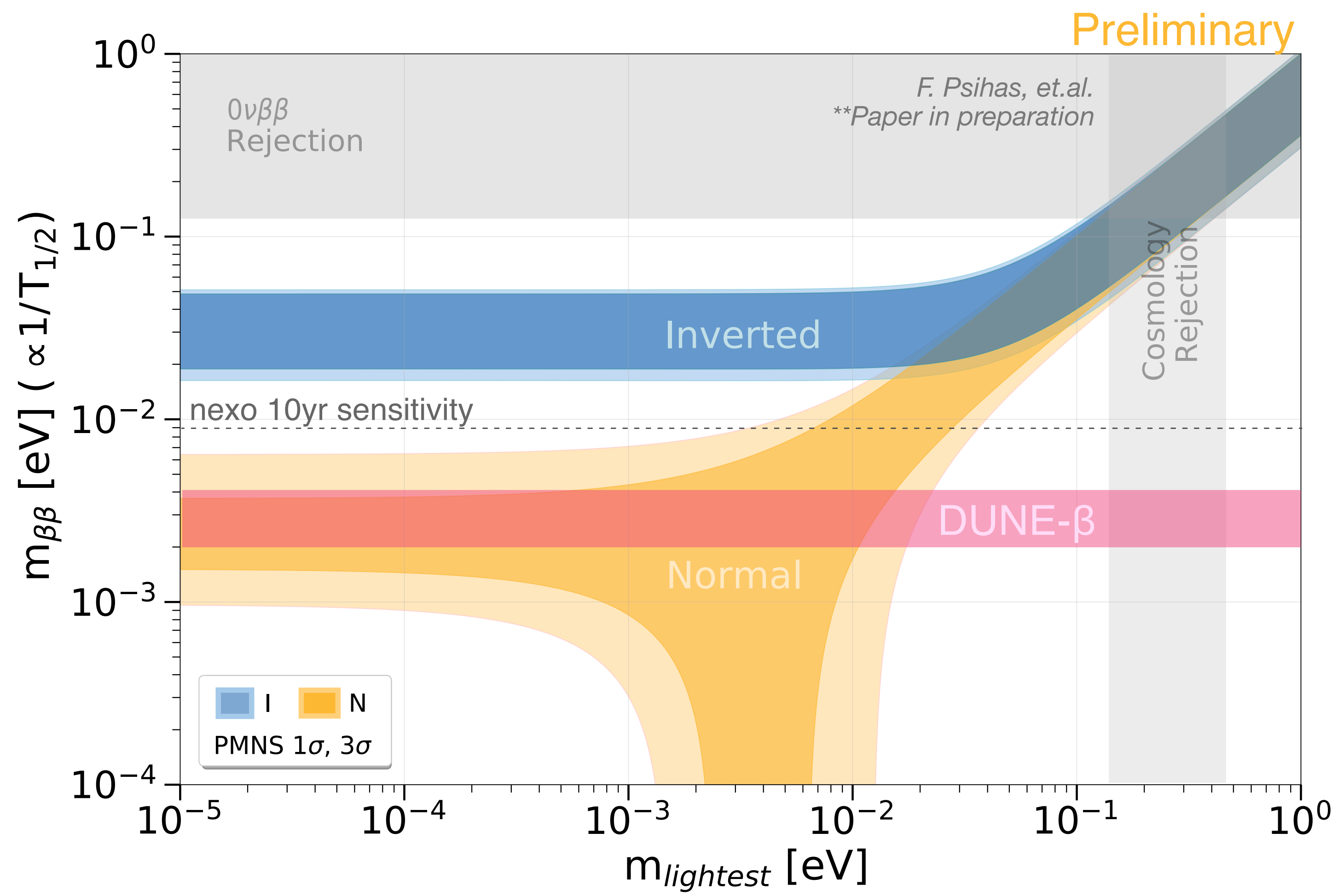
Nucl. Instrum. Meth. Phys. Res. A 279 (1989) 560-566



External Shielding ⚖️ Fiducial Volume



DUNE-β Potential



Original Plot: J. Detwiler, Neutrino2020